5.3 AGRICULTURAL WATER RESOURCES DECISION SUPPORT SYSTEM

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1. INTRODUCTION

The Bureau of Reclamation (Reclamation) is the largest wholesale supplier of water in the United States and serves more than 31 million people in the 17 contiguous Western States, providing more than 9.3 trillion gallons of water each year. Accurate, timely hydrometeorological information is essential for efficient water management. The National Weather Service (NWS), in partnership with other agencies, has installed a network of over 140 WSR-88D or NEXt generation weather RADar (NEXRAD) systems throughout the contiguous 48 states. Great potential exists for agencies such as Reclamation to apply enhanced NEXRAD precipitation products for improving the efficiency of water resource operations.

One example of Reclamation's efforts to make operational use of NEXRAD precipitation estimates is the development of the Agricultural WAter Resources Decision Support (AWARDS) system. The concept for the AWARDS system grew out of Reclamation's desire to conserve water by improving the efficiency of water use from Reclamation projects. Improved water use will often lead to better water conservation.

The AWARDS system is an automated information system on the Internet that was designed to assist water managers and users by providing easy access to rainfall and daily crop water use estimates. The purpose of the AWARDS system is to improve the efficiency of water management and irrigation scheduling by proving guidance on when and where to deliver water, and how much to apply.

2. THE AWARDS SYSTEM TECHNOLOGIES

Technologies used in the AWARDS system are:

- NEXRAD weather surveillance network.
- Automated weather station data networks.
- Computers and models.
- Geographic Information Systems (GIS).
- Evapotranspiration (ET) calculations.
- Effective Rainfall estimates.
- The Internet for water user access.

Figure 1 shows how these technologies are integrated in the current AWARDS system. The GIS data layers are updated for each AWARDS system project area as needed. The ET calculations are done each morning during the preparation of the daily Internet products.

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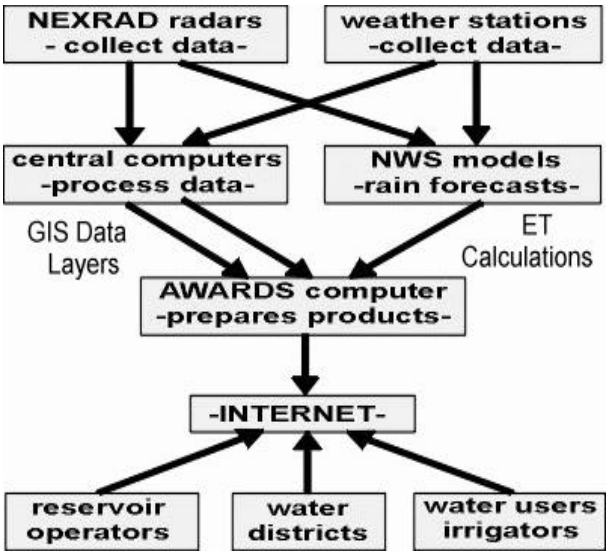

Figure 1. Schematic diagram of the AWARDS system

Each of the listed AWARDS system technologies are discussed in more detail in the following subsections.

2.1 NEXRAD Weather Surveillance Network

High resolution NEXRAD rainfall estimates are essential for the AWARDS system. The locations of the recently installed NEXRAD (WSR-88D) radars are shown in Figure 2. These radar systems were installed so that the radars' 230 km radius coverage areas overlap in most areas; however, terrain blockage is a problem in some areas of the western states. The Lugert-Altus Irrigation District below Altus Dam in southwestern Oklahoma was selected as the initial developmental area for the AWARDS system. Figure 3 shows the overlap of the 230 km radius coverage circle in this area. The town of Altus is about in the center of the District.

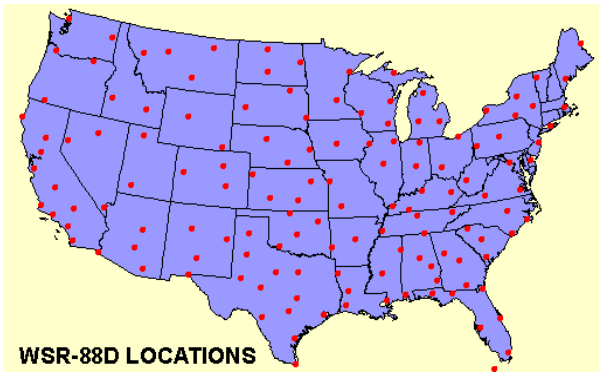

Figure 2. Locations of over 140 NEXRAD or WSR-88D Doppler radar systems within the contiguous 48 states.

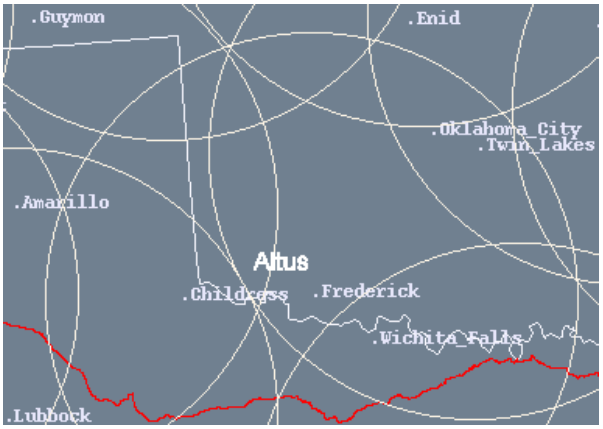

Figure 3. Overlap of the 230 km radius coverages from four NEXRAD systems over the area around Altus, OK.

AWARDS systems implemented east of the Continental Divide use the NEXRAD Stage III multi-sensor (radar and gage) hourly product produced by the NWS River Forecast Centers (RFC). In particular, Reclamation projects in Oklahoma and New Mexico utilize the WSR-88D Stage III product obtained in near real time from the NWS's Arkansas-Red Basin and West Gulf RFCs, respectively. The support of these RFCs for the AWARDS system is greatly appreciated.

Reclamation is also obtaining the WSR-88D Stage III product from the NWS Northwest RFC; however, its accuracy over southwestern Oregon is not sufficient for operational needs. This result is due to the mountainous terrain, the location of the Medford WSR-88D at a high elevation location, the orographic type of precipitation, the NWS's use of the standard Z-R relationship with no range correction, and other factors. (The problem of obtaining WSR-88D based Quantitative Precipitation Estimates (QPE) over mountainous watersheds in the west is discussed in Hartzell et al., 2000.)

NEXRAD precipitation estimates are derived products produced by the NWS Radar Product Generators (RPGs). The radar reflectivity data are converted to rainfall rates using a *Z-R* relationship, and precipitation accumulations are then calculated (Crum et al., 1993; Klazura and Imy, 1993). Level I data are the analog signals from the Radar Data Acquisition (RDA) site, Level II data are the digital base data output from the RDA signal processor, and Level III data are the base and derived products/algorithm output produced by the NWS NEXRAD RPGs. Following are descriptions of the Level III Hourly Digital Precipitation (HDP) products.

Stage I: Stage I precipitation processing, also referred to as the NEXRAD Precipitation Processing Subsystem (PPS), runs on the NEXRAD computers (RPGs) located at the NWS local Weather Forecast Offices. NEXRAD Doppler radar systems measure equivalent reflectivity factor (Z_e) data as input to the PPS. This input has 256 intensity levels and a spatial resolution of 1 deg by 1 km range. The PPS produces the Hourly Digital Precipitation (HDP) array product for each radar system. This HDP product is identified as Stage I, which uses the Hydrologic Rainfall Analysis Project (HRAP) grid cells (Greene and Hudlow, 1982), sized at about 4 km x 4 km.

Stage II: Stage II precipitation processing recreates the HDP array using Stage I output in combination with hourly rain gage data. The rain gage data are used to adjust the radar data, using an objective analysis procedure, to create a multi-sensor hourly precipitation estimated accumulation analysis. At present, the Stage I output data are passed to the NWS RFCs for follow-up Stage II and Stage III precipitation processing.

Stage III: Stage III processing mosaics (merges) the Stage II analyses from individual radars, using tools that allow the forecaster to analyze and edit the individual multi-sensor analysis to create an HDP array product for the entire RFC's area of responsibility. These data are generated into Network Common Data Format (NetCDF) or xmrg (binary file format) files.

The Stage III digital array of hourly NEXRAD precipitation estimates are automatically collected into the AWARDS computer via File Transfer Protocol (FTP) from the RFCs within 45-minutes of the next hour. Once a full 24 hours are accumulated, computer programs produce 24-hour customized image summaries.

2.2 Automated Weather Station Data Networks

Automated weather stations in operational and developing AWARDS areas collect and transmit surface weather data via radio signal, phone line, cellular phone, or satellite to local computer systems. These data are then automatically collected from the sources, via FTP, into the AWARDS computer. In some cases, 5-minute data are acquired; in others, only full 24-hour accumulations are available. These data are normally accessible in the early morning, allowing sufficient time to prepare ET charts for the Internet site maps. Networks of such monitoring station networks include:

- Reclamation Agrimet and Hydromet networks
- NWS automated weather stations
- Oklahoma Mesonet environmental stations
- State automated climatological data networks
- AWARDS/ET Toolbox weather stations
- Remote Automated Weather Stations (RAWS)

The best example of such an automated network of environmental monitoring stations in use with an AWARDS system is the world class Oklahoma Mesonet (http://okmesonet.ocs.ou.edu/). This network of 114 automated stations was designed and implemented by scientists at the University of Oklahoma and Oklahoma State University (Crawford et al., 1992). The locations of the Oklahoma Mesonet stations are shown in Figure 4.

In New Mexico, Reclamation partnered with the Middle Rio Grande Conservancy District (MRGCD) to implement the AWARDS system for their district, which extends from Cochiti Dam (located north of Albuquerque) southward to the Bosque del Apache National Wildlife

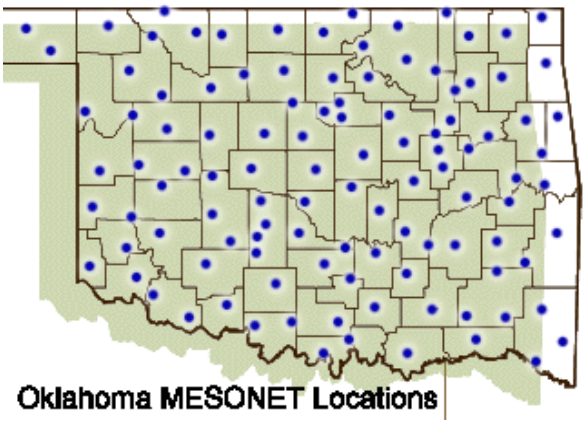

Figure 4. Locations of the 114 Mesonet automated weather stations covering Oklahoma.

Refuge. (This area is shown in Figure 1 in Paper 5.4 of this Preprint, Brower et al., 2000.) As part of this project, 10 automated weather stations were installed along the Rio Grande within the MRGCD. Data from these stations are downloaded to the AWARDS system computer on an hourly basis. In addition to being available for project use, the NWS Weather Forecast Office in Albuquerque imports the hourly rainfall data, thereby making these data available to the West Gulf RFC for producing the NEXRAD Stage III products over central New Mexico.

2.3 Computers and Models

An AWARDS system computer, a UNIX workstation, automatically collects digital format data files of NEXRAD Stage III rainfall estimates, weather station data, NWS quantitative precipitation forecasts (QPF), and model forecast parameters from the central computers. The UNIX workstation prepares the rainfall image and chart products, processes the ET calculations, and provides them in near real-time for Internet access.

The NWS 24-hr QPFs for the Arkansas-Red Basin and the Rio Grande Basin are obtained via automatic FTP from the Arkansas-Red Basin RFC in Tulsa, OK, and West Gulf RFC in Fort Worth, TX, respectively. These QPFs are received twice daily and posted on the AWARDS systems' pop-up crop water use charts.

AWARDS system HRAP grid rainfall estimates and ET products for the Rio Grande are imported to the Upper Rio Grande Water Operations Model (URGWOM) via RiverWare, which is a water distribution model for operations, scheduling, and planning. These models are discussed in Brower et al (2000).

Finally, NWS eta model 40-km gridded parameters from the 00 UTC model run are automatically collected from the National Centers for Environmental Prediction (NCEP). These data are used to make 24-hr ET forecasts over the project areas.

2.4 Geographic Information Systems

Various Geographic Information System (GIS) data resources are used, such as watershed, hydrologic, political boundary, irrigation district conveyance system, and other features, for developing the base maps for the AWARDS system. Such data sets are becoming more widely available on the Web and through media releases and products developed by local sources. In 1999, data and metadata (data about the data in the form of descriptions of the contents data sets) are more and more common. The need for tedious digitizing is rapidly becoming a task reserved only for new data layer development and not for common base mapping and standard products available in regional and national products thanks to increased data sharing. Access to greater types of data products and shared special, one-of-a-kind data layers has greatly empowered spatial data analysis involved in the AWARDS system.

Federal agencies delivering data products used in the AWARDS system include the U.S. Geological Survey [National Mapping Information, GeoData, EROS data center, etc.], National Resources Conservation Service [Maps, Facts and figures Web page], and the U.S. Department of Agriculture-Agricultural Research Service. Spatial data clearing houses are making the acquisition of data considerably easier to download. In addition, several watershed modeling systems now offer accumulated data sets suitable for use within the AWARDS system that are available on CD ROM or other popular delivery media as a "one-stop data-shop". An example is the BASINS Model Version 2.0 GIS data set (U.S. Environmental Protection Agency, Nov. 1998).

Local site information typically comes from the irrigation districts or contracted data providers as a special product, which is often a registered Computer Assisted Design (CAD) exchange or popular desktop GIS file format. Examples of this type of data include crop mapping and land use maps.

GIS systems are used to examine and perform analyses used by the AWARDS system. Analysis capabilities permit the partitioning of information for use by the AWARDS and ET Toolbox (Brower et al., 2000) elements of the system. For example, the land cover map can be reorganized to match the HRAP nominal 4 km x 4 km grid, the data are displayed and the coordinates are sent to a file format that is capable of being added to the Web Decision Support System (DSS) imagery. Additional analyses include watershed delineation and other spatially based operations to package the data in a visually compact way, and carry the attributes to pop-up text and detailed graphics.

An additional use of GIS technology is the use of Digital Elevation Model (DEM) data to develop hillshade backdrop maps to increase the "realness" of the background image to provide spatial reference. A very effective visual combination is the hillshade image coupled with a ramped elevation map that creates a quasi 3-D effect. These types of GIS-based products are output as standard graphics files (gif, tif, eps) and used in the development of the Web based interface.

2.5 Evapotranspiration Calculations

There are various methods available for calculating ET. Generally, either the Kimberly Penman equation (used in Oklahoma and Oregon) or a modified version of the Penman equation (used in New Mexico) are used in the AWARDS system for calculating reference evapotranspiration (Et). These values are empirically derived from experimental data based on an alfalfa referenced or grass referenced method that combines energy balance and heat and mass transfer functions (ASCE, 1990). A crop coefficient (Kc) is applied to the Et to determine the daily ET, in inches, using the formula:

ET = Kc x Et (reference)

The crop coefficient, Kc, is based on the ratio of an estimated ET, as measured by lysimeter in the field, to Et, as calculated from a Penman equation. Crop coefficients are normally derived in conditions where crop growth is not limited by physiological factors, available moisture, disease, or other factors that might hinder plant growth. Graphs of crop coefficients can be presented as a function of time, seasonal growth stages, percent of effective cover from zero to 100, or Growing Degree Days (GDD). In most of the AWARDS project areas, the GDD method is used. A physiological clock can be developed based on GDD, since plant development depends on heat units. Coefficients as a function of GDD developed under a particular climate condition can easily be transferred to different climate areas.

GDDs are accumulated heat that will contribute to plant growth and development from the period of planting until harvesting, or bud break to defoliation. An averaging method for calculating GDD is:

GDD = ((Daily Maximum Temperature + Daily Minimum Temperature) / 2) - Base Temperature

where the maximum and/or minimum temperatures are replaced with cutoff temperatures when limits are exceeded. Negative GDD values are prevented.

2.6 Effective Rainfall Estimates

Not all rainfall can be used by crops and other vegetation. This is especially true for rainfall events where the daily accumulation exceeds 0.50 inch. Therefore, the AWARDS system includes an effective rainfall estimation procedure for the 24-hr NEXRAD rainfall accumulations for each HRAP 4 km x 4 km grid cell within the area of interest (e.g., an irrigation district). Effective rainfall is currently estimated using an incremental percentage technique developed by Reclamation for monthly water resource calculations (ASAE, 1983). This technique does not allow for soil, slope, and vegetation coverage. Further research on daily effective rainfall estimating is required.

2.7 Internet for Water User Access

Reservoir operators, water managers, and on-farm water users access the AWARDS system products via the Internet. These products are available from Reclamation's convenient and user-friendly Web page (http://www.usbr.gov/rsmg/nexrad/). User requirements to access the AWARDS system are a computer system and a subscription to an Internet service. The AWARDS Web site is best viewed with either Netscape or Internet Explorer.

The Hyper Text Markup Language (HTML) Web page is constructed to place references to all images and links, including the context sensitive areas of images that are the basis for the user interface to the AWARDS and ET Toolbox. The end products (HTML, images and text files) are then transferred to the appropriate data directories using an automatic FTP process. The previously computed products remain in place and active until the automated timed execution of a new data gathering, data processing and file transfer effort. At that time, scripts are executed in logical sequence with error checking to develop the new products during a window of data availability and replace the previous data.

Information that is not included in the AWARDS system is the amount of water that on-farm users added to their crops through irrigation. Therefore, they will need to use the AWARDS system effective rainfall, ET, and forecast information available for each HRAP grid cell, along with a checkbook-type water accounting method, to determine when and how much water to add to their fields. Benefits from such a practice should reduce their operating costs and increase crop yields and profits.

3. HOW THE AWARDS SYSTEM WORKS

Figure 1 showed a schematic of the AWARDS system, which summaries how it works. The AWARDS system automatically integrates 1-hour and 24-hour NEXRAD rainfall estimates.

with 24-hour surface weather station data:

- mean temperature
- mean relative humidity
- mean wind speed
- rain gage rainfall accumulations
- total solar radiation

and uses the NEXRAD radar rainfall estimates and surface weather station data with:

- crop ET equations
- local terrain and soil information
- effective rainfall estimation procedures
- local daily max/min temperature normals
- quantitative precipitation forecasts (QPF)
- eta model forecast parameters for ET
- watershed/reservoir systems
- irrigation water distribution systems

to provide the water managers and users with:

- NEXRAD rainfall and watershed rainfall water

volume estimates
- effective rainfall estimates
- ET estimates and forecasts for determining crop water use requirements

4. AWARDS SYSTEM EXAMPLE

The AWARDS system example selected was for southwestern Oklahoma on 22 June 1999. Figure 5 shows the 4 km x 4 km grid of 24-hr NEXRAD Stage III rainfall estimates. As stated earlier, hourly Stage III digital data are obtained via FTP from the Arkansas-Red Basin RFC. The hourly data are accumulated until the local time day is complete, and then the 24-hr NEXRAD image is created. However, related hourly rainfall accumulation images are available to users via the Internet in near real time. Also shown in Figure 5 are the 24-hr Oklahoma Mesonet gage accumulations (+ signs) that are obtained each hour via FTP from the Oklahoma Climatological Survey. The other values in the figure are centers of either high or low Stage III rainfall estimates.

Figure 5 shows a significant convective storm event over Altus Dam and the northern portion of the Lugert-Altus Irrigation District (dashed line), as well as widespread lighter rainfall. The watershed above Altus Dam, also shown in the figure, is divided into three subbasins. The Stage III mean estimated rainfall is given for each subbasin (e.g., the mean 24-hr rainfall for the eastern subbasin was 0.49 in). The mean rainfall for the entire basin was 0.17 in. Pointing the computer mouse to inside the dashed line area and clicking the mouse will bring up an enlargement of this area.

Figure 6 shows a portion of the enlarged area covering the Lugert-Altus Irrigation District. NEXRAD Stage III estimated 24-hour (midnight to midnight local time/CDT) rainfall (in.) is given for each HRAP grid cell (about 4 km x 4 km). Also shown (at + signs) are the locations of two Oklahoma Mesonet weather stations, and the 24-hr rainfall accumulations measured by the gages. Even though gage measurements have their own problems due to wind speed and point measurements (Larson and Peck, 1974), the agreement between the gage values and the surrounding Stage III grid cell values is good.

The irrigators can click a computer mouse on the HRAP grid cells within the dashed line boundary for pop-up estimated Crop Water Use (ET) charts, and can click on the Oklahoma Mesonet weather stations for pop-up Daily Weather Data charts. Examples of these Crop Water Use and Daily Weather Data charts are shown in Figures 7 and 8, respectively.

Daily crop water use for the northern half of the Lugert-Altus Irrigation District is determined using data from the Mangum Mesonet weather station, and the southern half using data from the Altus Mesonet weather station. If necessary, an averaging algorithm could be implemented to better establish the ET for each cell as calculated by the two weather stations. Averaging was not used in the Lugert-Altus Irrigation District because minor variations exist in the weather data between the two stations.

The primary crop in the Lugert-Altus Irrigation District is cotton, which was planted during the month of May in 1999. The daily crop water use is calculated for each of the three planting date ranges that are centered on the "start date" listed in the figure (e.g., 508 is May 8th). This calculation is made using the kimberly Penman combination reference ET method (ASCE, 1990). A crop curve based on GDD was implemented as suggested by researchers (New, 1997) at the Texas Agricultural Extension Service.

In this example, the quantities (in) are shown in Figure 7 for the past 4 days (June 19-22). A forecasted ET for June 23 is estimated by averaging the past 3 days use, and eta model forecast parameters are used for adjustment. The cover and terminate dates are shown for reference, and the summation of ET since planting and for the past 7 and 14 days is presented. The NEXRAD total daily rainfall quantities for the specified number of hours of data availability and an estimate of the effective 24-hr rainfall are also presented. Monthly NEXRAD rainfall totals for this cell are also displayed.

5. SUMMARY

The AWARDS system is an automated information system to assist water users by providing easy access to rainfall and daily crop water use estimates. The purpose of the AWARDS system is to improve the efficiency of water management and irrigation scheduling by providing guidance on when and where to deliver water and how much to apply. The AWARDS system was designed for use by reservoir operators, water district staff, and on-farm irrigators. Benefits of using the AWARDS system are:

- Access to NEXRAD radar rainfall and ET estimates.
- Improved efficiency in reservoir and river system operations, water delivery, and on-farm irrigation scheduling.
- Reduced operating costs and increased crop yields and profits.
- Water conservation to meet increasing demands and improve water quality.

The AWARDS system demonstrates a methodology that integrates NEXRAD based rainfall estimates with automated data networks, GIS, modern computer, communication, and Internet technologies for improved water resources management.

Reclamation currently has AWARDS systems in southwestern Oklahoma below Lake Altus, along the Rio Grande Basin from its headwaters in Colorado to Ft. Quitman, TX, and in western Oregon near Medford and Portland. The system in Oklahoma is operational, while the other are under development. The project along the Rio Grande includes the development of an ET Toolbox for use with the Upper Rio Grande Water Operations Model (Brower et al., 2000). Plans are being made to implement the AWARDS system in other areas of the west.

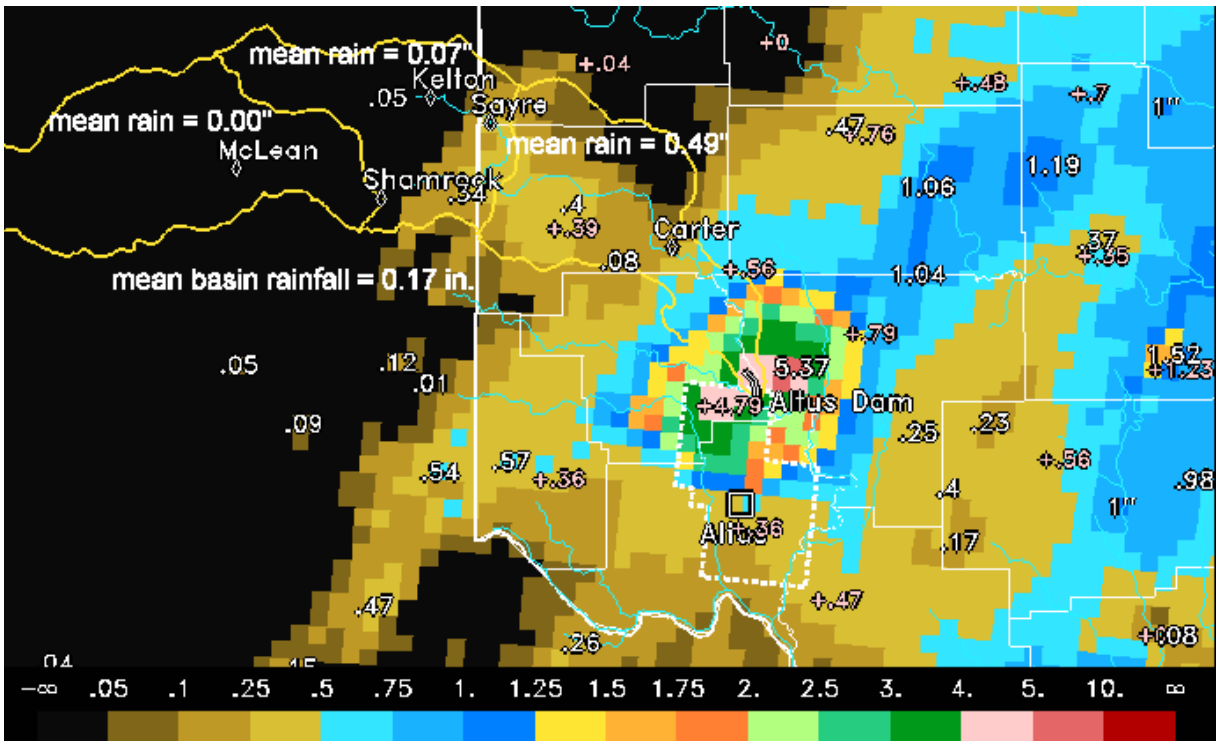

Figure 5. NEXRAD Stage III and Mesonet gage 24-hr rainfall accumulations for 06/22/99 CDT over SW Oklahoma. The area enclosed by the dashed line below Altus Dam is the Lugert-Altus Irrigation District.

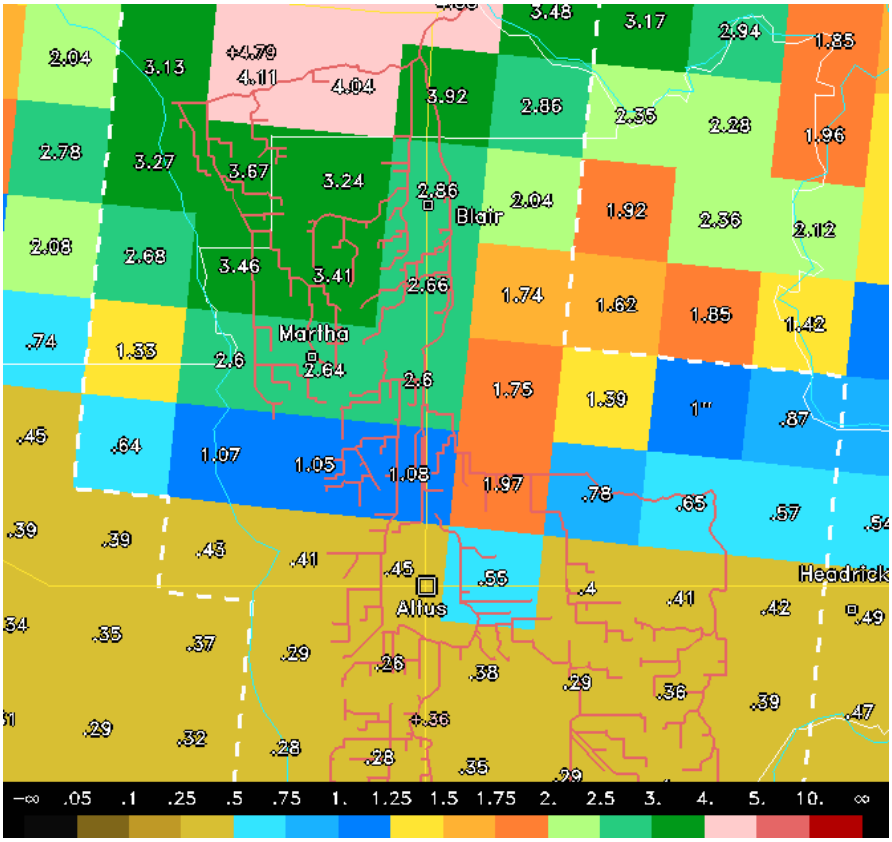

Figure 6. NEXRAD Stage III and gage 24-hr rainfall accumulations for 06/22/99 CDT over a portion of the Lugert-Altus Irrigation District in southwestern Oklahoma.

MANGUM, OK MESONET SITE - ESTIMATED CROP WATER USE - JUNE 23, 1999

CROP	START DATE	DAILY CROP WATER USE-(IN) PENMAN ET - JUNE 19	20	21	22	FORE-CAST JUNE 23	COVER DATE	TERM DATE	SUM ET	7 DAY USE	14 DAY USE
COTTON	508	0.09	0.04	0.03	0.02	0.03	805	1001	1.7	0.4	0.8
COTTON	513	0.08	0.04	0.03	0.01	0.03	810	1001	1.5	0.3	0.7
COTTON	520	0.07	0.04	0.02	0.01	0.03	816	1001	1.1	0.3	0.6
NEXRAD HRS AVAIL		14	24	24	24	QPF	QPF valid till 6am tomorrow				
TOTAL RAIN		0.10	0.39	0.51	4.11	0.35					
EFFECTIVE RAIN		0.10	0.39	0.48	2.26	0.35					

NEXRAD MONTHLY TOTAL RAIN:

JANUARY	1.85
FEBRUARY	0.13
MARCH	2.75

Figure 7. Example of a pop-up estimated Crop Water Use chart that included NEXRAD rainfall, effective rainfall, forecast daily ET, and 24-hr QPF. Grid cell number 161x40 is located over the Mangum Mesonet station.

MANGUM, OK - Mesonet Weather - 1999

	June 16	June 17	June 18	June 19	June 20	June 21	June 22
Max. Temp. (F)	78.3	77.2	86.4	96.3	84.6	81.9	76.6
Min. Temp. (F)	59.0	56.8	56.1	67.1	66.2	65.5	68.4
Avg. Wind (Mi/Hr)	7.8	4.3	7.8	7.4	4.3	5.1	6.3
Rel. Hum. (%)	70.9	67.0	65.4	68.4	82.0	93.8	94.6

Figure 8. Example of a pop-up Oklahoma Mesonet automated weather station Daily Weather Data chart.

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Partnerships with the NWS Arkansas-Red Basin RFC and the West Gulf RFC have been essential for this work (NEXRAD Stage III and QPF data). The Lugert-Altus Irrigation District in Oklahoma and the Middle Rio Grande Conservancy District in New Mexico have cooperated and provided user feedback on the uses of the AWARDS systems in their Districts.

Data from automated weather station data networks are provided by the Oklahoma Climatological Survey (Dr. Ken Crawford), University of Oklahoma; New Mexico Climate Center (Dr. Ted Sammis), New Mexico State University; and Reclamation's Agrimet Program (Peter Palmer). Information on crop coefficients for the ET calculations were provided by Oklahoma State University (Dr. Ron Elliot), Texas A&M University (Dr. Leon New) and New Mexico State University (Dr. Phil King). Many other organizations and individuals contributed to the AWARDS system and ET Toolbox development, especially in the areas of planning and technical support.

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